The Magnitude 6.7 Northridge, California, Earthquake of January 17, 1994

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Summary

The most damaging earthquake in the United States since 1906 struck northern Los Angeles on January 17, 1994. The magnitude 6.7 Northridge earthquake produced a maximum of more than 3 meters of reverse (up-dip) slip on a south-dipping thrust fault rooted under the San Fernando Valley and projecting north under the Santa Susana Mountains. The earthquake raised the mountains by as much as 38 cm. The shallow updip extent of this fault appears truncated by the fault that broke in the similarly sized 1971 San Fernando earthquake, the two faults abutting at 8 km depth. The Northridge earthquake caused many times more damage than the 1971 event primarily because its causative fault is directly under the densely populated valley, whereas the 1971 fault dips under the mountains and perhaps because of a higher stress drop in the 1994 earthquake. The Northridge earthquake is the sixth in a series of moderate-to-large events (M>5) to strike the northern Los Angeles basin since 1987. All these earthquakes are related to a broad system of thrust faults that accommodate the compression and uplift of the northern Los Angeles basin caused by a broad 160-km left bend in the Pacific-North American plate boundary called the Big Bend of the San Andreas fault. The Northridge earthquake emphasizes the hazard posed to Los Angeles by concealed thrust faults and the potential for strong ground shaking in Los Angeles and other cities to cause extensive damage and disruption.

Introduction

On January 17, 1994, at 4:30 a. m. (Pacific Standard Time, 12:30 UT) the first earthquake since 1933 to strike directly under an urbanized area in the United States occurred in a northern suburb of Los Angeles, California. This magnitude 6.7 *(1)* earthquake resulted from thrust faulting on a plane dipping down to the

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south-southwest beneath the northern San Fernando Valley (Fig. 1). It produced the strongest ground motions ever instrumentally recorded in an urban setting in North America and caused the greatest damage in the United States since 1906. Although the Northridge earthquake was the same size as the nearby 1971 San Fernando earthquake (M_W 6.7) (Fig. 1), it was much more damaging, in part because of its location directly beneath the San Fernando Valley and its closer proximity to communities in the Los Angeles basin.

The Northridge earthquake disrupted the lives and livelihoods of many of the residents of the Los Angeles area. Casualities included 33 dead as a direct result of the earthquake, more than 7,000 injuries treated at hospitals and over 20,000 homeless *(2)*. Financial losses have been estimated at $13-20 billion *(3)*. Sections of three major freeways were closed including the busiest highway in the country, Interstate 10. The losses continue to grow as damaged business districts lose customers, time is lost in longer commutes, and renters avoid even the undamaged housing in the epicentral region. In the midst of these losses, the gains made through earthquake hazard mitigation efforts of the last two decades were obvious. Retrofits of masonry buildings help reduce the loss of life, hospitals suffered less structural damage than in the 1971 San Fernando earthquake, and the emergency response was exemplary. The Northridge earthquake proved that preparing for earthquakes can greatly reduce the risk.

The earthquake brought home several important lessons for scientists and engineers as well as for the residents of southern California. Some were confirmation of the research results of the last decade of the National Earthquake Hazards Reduction Program. Thrust faults concealed below Los Angeles present a threat to the region approaching that posed by the San Andreas fault. When earthquakes occur directly beneath a city, it will be subjected to ground motions with peak accelerations approaching the force of gravity, exceeding the levels of shaking anticipated by building codes in some respects. Some of the lessons of the earthquake, especially about the effects of earthquakes, were more surprising. Ground failure induced by shaking can be as extensive as that caused by direct faulting, and the system of concealed faults under Los Angeles is more complex than previously thought, dipping both to the north and south. The engineering lessons, with an unprecedented number of engineered structures subjected to large ground motions, may be the most important of all. The wide-scale failure of 2-4 story apartment buildings built over parking garages has important implications for regional housing needs because of the pervasive use of such strucutres. Understanding the cause and correcting the weld fractures in taller, steel frame buildings in this earthquake will be essential to continue building in earthquake-prone regions.

To describe this earthquake, we first examine the tectonic setting of the event and the characteristics of its causal fault. We then examine the shaking and ground deformation produced by the event and analyze how well it can be explained by the known fault geometry. The damage to buildings and other structures can then be judged in relation to the shaking produced by the event.

Tectonic Setting of Los Angeles

The plate boundary between the Pacific Ocean and North American plates dominates the tectonics of much of California. The boundary is particularly complex in southern California because of a bend in the San Andreas fault that offsets the boundary 160 km in a left step (i. e., to the east when heading south) (Fig. 2). The northwestward motion of the Pacific Plate along the west-northwest-striking San Andreas fault requires compression of the crust around this bend *(4)*. More than 10 mm/yr of this shortening is accommodated on the system of east-striking thrust faults and folds of the Transverse Ranges and the Los Angeles basin *(5)* that we refer to as the Big Bend Compressional Zone. The zone includes many sub-parallel faults dipping both to the north and south, some that come to the surface and some that do not, broad folds and down-warps, interspersed by numerous Miocene to recent sedimentary basins. The interaction of these faults has yet to be understood in detail but probably no single fault dominates the compressional deformation in the way that the San Andreas fault principally accommodates the strike-slip deformation of California.

The longest thrust fault exposed at the surface in the Big Bend Compressional Zone is the Cucamonga-Sierra Madre fault that dips north under the highest and steepest mountains of the belt (Fig. 1, 2) with a geologically determined minimum slip rate of 3 mm/yr *(8)*. The 1971 San Fernando earthquake broke the westernmost 15 km of this fault system *(9)*. To the west of Northridge, this system splits into two surficial faults, the north-dipping San Cayetano fault and the south-dipping Oak Ridge fault. The world's thickest section of Pliocene sediments, **12** km in the Ventura basin, lies between these two faults *(10)*. Geodetic measurements have shown the Ventura basin to be one of the fastest deforming parts of California, closing at 8 mm/yr *(11)*.

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The 1994 Northridge earthquake occurred at the intersection of several mapped faults of the Big Bend Compressional Zone (Fig. ?). The nearest known south-clipping fault is the Oak Ridge fault to the west in the Ventura basin *(11, 12)*. The surficial expression of this fault ends 15 km west of the buried rupture of the Northridge mainshock. Above the northern part of the 1994 fault plane is the transition of the north-dipping Sierra Madre fault to the Santa Susana and San Cayetano faults (Fig. 2) *(13)*. The fault that moved in this earthquake does not extend to the surface and was not mapped before the event.

Recent moderate earthquakes in southern California (including the 1987 Whittier Narrows M5.9 event *(14,15)*) and an on-going analysis of geology and seismicity has revealed the potential for damaging earthquakes cm the concealed thrust faults of the Los Angeles basin *(16,7)* as well as the surficial faults of the Big Bend Compressions] Zone. The dense system of exposed and concealed thrust faults along the northern flank of the Los Angeles basin coupled with high geodetic rates of compression imply that the northern Los Angeles region faces one of the greatest seismic hazards in southern California *(17)*. A report in revision at the time of the Northridge earthquake had put the northern San Fernando Valley in the top one-sixth of southern California for seismic potential

(18). The risk (19) is even greater because these faults underlie the heavily urbanized sedimentary basins. While potential earthquakes along this zone may be smaller than expected strike-slip events on the San Andreas fault and each fault moves more slowly, in aggregate, they are more frequent and are occurring directly beneath densely populated, highly developed urban areas.

The Earthquake Source

Regional Seismicity.

Since 1920, eighteen moderate (M4.8-6.7) mainshock-aftershock sequences have occurred in the greater Los Angeles area (Fig. 1), Because only the 1971 San Fernando earthquake produced surface rupture, the association between a mainshock hypocenter and a nearby fault is usually inferred from the mainshock focal mechanism and the distribution of aftershocks. These earthquakes have occurred in two temporal and spatial clusters. The first was from 1920 to 1942 along the southern Los Angeles basin while the second, from 1970 to the present, is concentrated along the northern edge of the Los Angeles basin (20).

The 1971 San Fernando earthquake (M_W 6.7) (21) was located just northeast of the Northridge earthquake, also on a west-northwest-striking plane, but dipping down to the north, part of the Sierra Madre system that lifts up the San Gabriel mountains (Fig. 1, 2). Studies of that earthquake (22, 23) suggested that the western edge of the thrust fault was bounded by a north-northeast striking left-lateral tear fault, called the "Chatsworth trend". Other moderate earthquakes in this temporal cluster have occurred on the Sierra Madre fault (24), the Elysian Park fault system (25) and the Raymond fault (26). Besides the moderate earthquakes, the northern flank of the Los Angeles basin has sustained a high level of background microseismicity in the last decade (7). Focal mechanisms in the immediate vicinity of Northridge show thrust earthquakes in the north-dipping San Fernando rupture zone, its westward extension and near the Northridge mainshock fault plane. Strike-slip events continued along the Chatsworth trend (27).

The Northridge earthquake had no immediate foreshocks although the aftershock zone averaged 22 events/ yr from 1981-1993 above Ml .7. Ten days before the event, a swarm of small earthquakes (including four M3.0-3.7) occurred in the Santa Monica Bay, 30 km south of the Northridge hypocenter. The alignment of the epicenters suggests a shallow, south-dipping fault, parallel to the Northridge fault but offset at least 30 km to the south. Because they occurred on a separate fault and M≥3 events occur in the Los Angeles basin 5-10 times each year, we see no direct relationship between these events and the Northridge earthquake.

Mainshock Source Parameters.

The Northridge earthquake originated at 34° 12.53'N; 118° 32.44'W, about 30 km west-northwest of downtown Los Angeles at a focal depth of 19 km. The first motion focal mechanism shows almost pure thrust motion on a plane striking N70°-80°W and dipping 35°-450 down to the south-southwest (Fig. 1). Models of the long-period waveforms and geodetic offsets suggest similar fault orientalions, although several of the longer-period solutions have a more northerly strike. The earthquake began at the down-dip, southeastern corner of this plane and ruptured up to the northwest for about 15 km. This suggests that rupture began on a plane striking N75°W and bent to the north as it propogate/to the west. We have no evidence of slip above about 8 km depth.

Models of both body wave and surface wave data give a seismic moment of (1.2 ± 0.2) x 10^{19} Nt-m and all of the geodetic models suggest similar moments. All of these models imply a larger amount of slip than usually seen on thrust faults only 15 km long. The maximum slip during the Northridge earthquake exceeds 3 m and is concentrated 5-10 km northwest and updip of the hypocenter *(28)*. This patch of slip appears to have produced a distinct, second pulse of energy about 2 seconds after the start of the earthquake which led to early, public media reports that the Northridge earthquake was actually two events.

Aftershocks.

The 2000 aftershocks of M>1.5 recorded in the first 3 weeks of the sequence (Fig. 3) *(29)* form t wo zones. One, associated with the mainshock rupture, outlines an approximately square zone extending about 15 km west-northwest from the mainshock epicenter and about 15 km to the north-northeast. A second zone, about 15 km long and 10 km wide, northwest of the mainshock zone developed after the second largest aftershock occurred 11 hours after the main-shock. All the aftershocks from January 18 to June 1 occurred within the area defined during the first 24 hours of activity *(30)*.

The mainshock began at the southeastern end of the aftershock zone. The aftershocks define a 35°- 45° dipping plane from 19 km to about 8 km depth (Fig. 3). The southern half of this zone lies under the San Fernando Valley. The plane is topped by a cloud of aftershock hypocenters resulting in diffuse deformation of an overlying anticline. The westernmost 15 km of the aftershock zone forms an approximately vertical distribution beneath the Santa Susana Mountains, appearing to be cm secondary faults that did not rupture in the mainshock. Aftershocks began to occur in this region only after the second largest aftershock had occurred. It had a local magnitude of 5.6 at a depth of 11 km, and a thrust-faulting focal mechanism similar to the mainshock. The largest aftershock was a M5.9 event that occurred one minute after the mainshock along the eastern edge of the aftershock zone. By fitting a decay rate equation to the aftershock data from the first 12 weeks, we can estimate the number of aftershocks to expect in the future *(31)*. The Northridge aftershock sequence has an overall greater productivity than average but is dying off slightly more quickly than average for California aftershock sequences. The probability of one more aftershock above magnitude 5 between June 1, 1994 and May 31, 1995, is 50%.

The 1971 San Fernando earthquake occurred on a fault parallel to the Northridge fault but dipping in the opposite direction, down to the north (Fig. 3). The 1994 fault dips up to the north towards the 1971 plane (Fig. 3). Although the Chatsworth trend bounded the 1971 aftershock zone to the west (22), we do not see a similar structure in the 1994 aftershocks. Rather, the probable 1994 mainshock rupture plane extends about 15 km in an east-southeast direction and is bisected by the Chatsworth trend. Northridge aftershocks occur within the hanging wall near the Chatsworth trend; however, unlike 1971, few of the 1994 aftershocks have strike-slip mechanisms and the few that do, do not form a lineation of any orientation within the zone. It thus appears that the 1994 mainshock broke across the Chatsworth trend and produced slip on both sides of that tear fault without reactivating it. Most of the 1971 aftershocks defining the Chatsworth trend were shallow (<10 km) so this structure might exist on] y in the hanging wall of the 1994 earthquake *(22)*.

Earthquake Effects

Crustal Deformation

Elastic strain released by the Northridge earthquake measurably deformed the crust in a 5,000 km^2 area surrounding the epicentral region. Observations of the displacements of 25 survey stations determined using GPS (Global Positioning System satellites) before and after the earthquake show that stations were lifted up more than 50 cm, and displaced horizontally as much as 21 cm (Fig. 4). The vertical displacements along the causal fault during the earthquake raised the Santa Susana Mountains and the northern San Fernando Valley. In addition to the ground motion directly attributable to slip on the fault, seven stations to the north and west of the rupture show several cms of westward motion that cannot be modeled by either the mainshock or the significant aftershocks.

Continuous high-precision strain measurements were made in boreholes before, during and after the Northridge earthquake at distances of 74 and 196 km. The coseismic, peak dynamic strains observed in the boreholes exceeded 10 micros train with net offsets of 21 nanostı ain (extension) and 5 nanostrain (compression), respectively. These offsets are consistent with the moment of the earthquake, No systematic change in strain above the background noise of 0.1 nanostrain occurred during the hours to milliseconds before the event, Some minor relaxation (rebound) occurred in the few minutes after the main rupture.

Ground Shaking

The Northridge earthquake produced very strong ground motions across a significant part of the Los Angeles metropolitan area (Fig. 4). It also produced an unprecedented number of important strong-motion accelerograms, more than 200 free-field recordings *(32)*. The high level of damage in this earthquake resulted in large part from the dense population in immediate proximity to the earthquake source. This is reflected in the strong motion data set, with many more strong motion recordings within 25 km of the source than ever before recorded for a single event.

The peak horizontal accelerations recorded in this earthquake were larger on average for its magnitude than the peak accelerations recorded for other reverse-faulting earthquakes (Fig. 5). However, how the accelerations diminish with distance from the source in this type of earthquake is not well established due to the paucity of data, especially at very short distances. Although early reports suggested that high vertical accelerations may have contributed to the extensive damage in the Northridge earthquake (a report adopted by many who confused the vertical motion of the fault block with vertical shaking at a site), the ratio of peak vertical to peak horizontal acceleration in this earthquake is not anomalous. The vertical *and* horizontal ground accelerations, velocities, and displacements were large, but the average peak accelerations are no more than one standard deviation above the mean of the average in other earthquakes. The systematic variation in overall acceleration levels between earthquakes has been recognized for some time *(33)* and extensively analyzed (34).

For different sites in one earthquake, the most important factor controlling the amount of strong shaking is the distance of the site from the fault plane. The sites closest to the Northridge earthquake are those north of the hypocenter because the plane shallows to the north. In addition to source distance, a number of other factors contribute to the variability of ground motions apparent in Fig. 4 and 5. Directivity *(35)* probably increased the ground motions at sites to the north of the epicenter as the fault rupture propagated toward them. In the region 10-15 km north-northeast of the epicenter, where we would expect the combined effects of radiation pattern *(36)* and directivity to be maximized for this fault geometry, the recorded ground velocities are among the largest ever recorded. In fact, the recorded peak horizontal ground velocity at a free-field site near the county hospital in Sylmar (15 km north-northeast of the epicenter) was about 130 cm/s; the peak velocity was over 170 cm/s at the Los Angeles Department of Water and Power Rinaldi Receiving station several km south of the hospital *(37)*. The ground velocities in this region are dominated by a single, large amplitude pulse indicative of source directivity. For many larger structures, peak ground velocity is a better measure of damage potential than is peak ground acceleration.

As in other earthquakes, soft soils may have produced higher ground motions locally *(38)*. Several of the larger peak accelerations *were* located south of the epicenter where the large amplitudes were likely controlled by propagation and site effects rather than source radiation alone. The high frequency variations in the peak accelerations at these sites lead to lower peak velocities for the same or higher peak accelerations than at the northern sites. Farther south in the northern Los Angeles basin, the generation of surface waves along the edge of the basin may have played a role in the high accelerations and extensive damage in Santa Monica, Hollywood and south-central Los Angeles *(39)*. When the data on site conditions have been collected, the Northridge earthquake will provide an opportunity to learn more about the effect of site conditions on ground motion.

Ground Failure

In contrast to the 15 km of well-defined surface faulting in the 1971 San Fernando earthquake (9), the Northridge event produced no clear evidence of primary surface rupture, Slip on concealed faults by definition does not come to the surface, but it can result in coseismic folding above the fault plane producing a broad zone of surficial deformation. This deformation in the Northridge earthquake was concentrated in three locations -- near the epicenter, in Granada Hills just east of the inferred rupture surface, and along the north flank of the Santa Susana Mountains (Fig. 4).

Most of the surface displacements in these features are extensional, with cumulative displacements across zones of fractures rarely exceeding a few tens of centimeters. Where these fractures cross streets and sidewalks, they are refracted into complex arrays of pavement cracks and buckles, spalled and extended curbs, and tented sidewalk slabs; many of these features probably resulted from decoupling of the pavement from the ground below. Most of the deformation appears to be attributable to ground failure from strong shaking, differential compaction of loose sediment in the subsurface, or liquefaction *(40)*. However, we cannot rule out the possibility that some of the deformation in Granada Hills and along the northern flank of the Santa Susana Mountains is a response to folding during coseismic uplift of the mountains and northern San Fernando Valley.

Although displacements on the secondary ground ruptures are small, the linear extent of these zones is comparable to what might be expected for a surface faulting earthquake of similar magnitude. They also caused significant damage in densely developed areas *(41)*. The ability to recognize zones of secondary ground deformation before the next major earthquake represents a significant challenge to geologists. However, deformation clearly occurs repeatedly in the same areas. Secondary fractures are commonly aligned along fault zones or the axial surfaces of folds, and preferentially occur in regions underlain by soft sediment. In many cases, these zones have subtle topographic expression.

Liquefaction.

Liquefaction produced sand blows and other evidence of permanent ground deformation in Holocene alluvial deposits and filled land at several sites within 48 km of the epicenter (Fig. 4), damaging pipelines, water-supply channels, filtration facilities, parking lots, residential and commercial buildings, storm-drains and flood-control debris basins, However, the Northridge earthquake caused much less ground failure due to liquefaction than many other earthquakes of its size. The near-surface deposits in much of the western San Fernando Valley consist mainly of cohesive clay and clayey silt. Cohesive water-saturated sediment is not generally susceptible to liquefaction, which might explain the relatively sparse incidence of observed liquefaction-related damage in the epicentral area.

A cluster of sites 10-15 km northeast of the epicenter (Fig. 4) experienced liquefaction both in 1994 and in the 1971 San Fernando earthquake but with smaller displacements at the ground surface in 1994. Follow-up studies at these sites will be required to discern if the smaller ground displacements are best ascribed to increased relative density caused by ground shaking, lowered ground water table that increases the effective normal stress acting on elements of soil at depth, the shorter duration of shaking in 1994 compared to 1971 *(42)* or to engineered countermeasures taken to mitigate the liquefaction hazard.

Regional liquefaction hazard maps of the Los Angeles region assume that highly liquefiable, loose, clay-free, sandy, alluvial fan deposits or narrow channel deposits of former streams could experience liquefaction when associated with persistent shallow ground water. However, in many areas, including the western San Fernando Valley, these deposits are not mappable from surface exposure. Thus the regions of persistent shallow ground water (<3 m) were mapped to highlight areas where additional site-specific studies might be advisable to determine if susceptible deposits were present *(43)*. Additional studies of the permanent ground deformation described above are needed to determine if liquefaction-induced ground failure, settlement, or seismically-induced compaction of small bodies of loose sediment in a dry state could explain their occurrence. For much of the epicentral area, if ground water levels are maintained at or below present levels, the risk of liquefaction in buried channel deposits for a comparable sized earthquake is probably at acceptable levels,

Earthquake Damage to Structures

Structural damage was extensive but not devastating. About 3,000 buildings were deemed unsafe by building inspectors, only a small fraction of the total inventory in the region of strong shaking, and many of these are repairable. Losses to the contents of buildings were major, probably exceeding the total cost of the structural damage, Significant damage also occurred to bridges, a major dam, electric power facilities, and water and gas pipelines. Restoration of utilities was rapid, because of the use of redundant and backup systems, The Los Angeles high-rises were outside the region of very strong shaking and were mostly unaffected, as was the new subway.

[Unreinforced masonry buildings (URMs) cracked and parts of their walls fell outward, but few life threatening collapses to occupants occurred, Many of these buildings are residential and not one life was lost. However, few URMS exist in the epicentral region. Most existing URMS were built before 1933, the year the Long Beach earthquake damaged many such structures, and the epicentral region had few buildings at that time. A URM retrofit program instituted by the City of Los Angeles has strengthened 4,000 buildings and helped to prevent life loss during the Northridge earthquake. Damage to URMs occurred both in Los Angeles where most of these structures are retrofitted and in adjacent cities without retrofit programs, so documentation of the benefits of retrofit can be made,

Nonductile reinforced concrete buildings behaved poorly with partial collapses of a multi-story medical clinic and a mall, both high-occupancy structures during business hours. In addition, a hotel, condominium tower, hospital and office building were left severely damaged. Many older reinforced concrete buildings built before the mid 1970's, when lessons from the 1971 San Fernando earthquake were incorporated into the codes, are nonductile (i.e., brittle) and carry significant risk. Modern reinforced concrete structures fared fairly well with the exception of precast concrete parking garages, 6 of which partially collapsed. Factors in these collapses may include connection inadequacies and poor lateral deformation capability of components intended to carry only vertical load.

Wood frame buildings, both old and new, showed deficiencies. Inadequate bracing in parking areas in the ground story of multi-story residential structures caused some ground story collapses and the deaths of 16 people at one apartment complex. Reliance on brittle materials such as stucco for lateral strength proved unwise as these materials broke down under cyclic loading. The trend toward fewer, heavier shear walls created large overturning forces and caused base anchors to fail. Post-earthquake reconnaissance of damaged wooden buildings revealed that many were not constructed according to the approved plans, suggesting a lack of proper inspection. This poor workmanship was a major reason for much damage.

The structural behavior with the potentially greatest economic implications was the brittle fracture of welded connections in steel buildings, most often the beam-to-column connections which give a building its lateral earthquake resistance. Steel buildings are commonly believed to possess excellent ductility, but apparently the welding procedures in use do not achieve this desired behavior. Laboratory test results also sometimes show poor behavior, but not to the extent seen in the field. Although the problem seems serious, none of the 50 or so buildings identified with connection fractures collapsed or even developed a serious lean. Some damaged buildings are yet to be identified because the cracks are well hidden behind fireproofing and architectural finishing materials. Many aspects of the problem, including proper repair strategies, remain to be resolved.

Damage to furnishings, storage racks, ceilings, glass, piping and equipment was extensive. Although hospitals are designed for higher seismic forces than ordinary buildings, several were forced to close temporarily solely from nonstructural damage. This list includes the county hospital in Sylmar, an exceedingly strong post-1971 structure with steel shear walls, where a peak horizontal acceleration of 2.3 g was recorded on the roof. Schools suffered much nonstructural damage, and falling lights would have claimed lives had schools been in session. Water damage from broken piping required massive clean-up efforts in many buildings. Malfunctions of back-up power systems affected hospitals, telephone service, and emergency response operations.

Two major base-isolated buildings were shaken by moderate ground accelerations, reaching 0.5 g horizontal at one site, and performed well without damage. These buildings are supported on rubber pads which provide flexibility to isolate against horizontal ground motions. A critical design objective is to avoid excessive pad displacements, and this can be difficult if the ground motion contains a strong long-period component. The Northridge earthquake motions at the sites of the base-isolated buildings were deficient in long periods, so this successful experience does not prove them fail-safe. There were other sites with much stronger long-period ground motion, especially at the county hospital in Sylmar, and a base-isolated structure located there would have been tested severely.

The Northridge earthquake struck during California's ongoing seismic retrofit program for bridges which began after the 1989 Loma Prieta earthquake. Freeway bridges in California are typically reinforced concrete box girders supported on reinforced concrete columns, and seven such bridges collapsed. Five of these were of pre-1971 nonductile design and had been scheduled for retrofit, and the other two date to the mid-1970's and were of better design. One of the collapses was a high bridge, and excessive sway pulled the expansion joints apart causing decks to fall. inadequately reinforced columns caused the other collapses; the columns of the two more recent bridges were still substandard even though these two bridges had not been placed on the retrofit list. Several older bridges that had had their columns retrofitted by steel jackets performed well but did not experience the very strong shaking.

Of the more than 100 dams located within 80 km of the epicenter, only Pacoima Dam, a 111 m high arch dam (located 18 km from the epicenter but only 10 km from the probable fault plane), suffered notable damage. Recorded accelerations as high as 2 g on the canyon walls triggered numerous rock falls. A 5 cm wide crack opened at the left abutment of the dam because of movement of the adjacent rock mass, and cracks in the upper part of the dam were testament to the strong shaking. The water level during the earthquake was low, and since Pacoima Dam is operated for flood control, high water is infrequent. After an embankment dam liquefied and was nearly overtopped during the 1971 San Fernando earthquake, the California dam regulatory agency has overseen seismic improvements at 27 dams in the region, including installation of rock anchors on the left abutment of Pacoirna Dam which helped to limit the rock movement there during the Northridge earthquake.

Discussion

Detailed studies of major earthquakes through both the earth sciences and engineering provide us the knowledge to mitigate future earthquake hazards. These studies include characterization of the earthquake source (using the geologic and seismologic record to estimate how large an earthquake can happen with what probability), prediction of the ground motions (given an earthquake of some size at some distance, how will the ground actually move under your building), and building response (how do buildings behave subjected to those ground motions). All of this knowledge is necessary to ensure the safety of our buildings and structures. We need to insure that the lessons learned from the Northridge earthquake lead to real improvements in our built environment. Some of the conclusions from the earthquake were expected from recent research and some surprised us. If we implement these lessons, we will protect the lives not only of Californians but of many other regions of the United States and the world at risk from earthquakes.

Concealed faults beneath Los Angeles have been recognized from distributions of microseismicity (7), and detailed maps of overlying geologic structures (15, 44). Geodetic data have been used to infer rates of motion that together with seismological or geological evidence of the location of the faults can provide an estimate of the hazard from the faults. Such studies have found several probable concealed thrust systems in the Los Angeles basin south of the San Fernando Valley. However, it is notable that neither of the faults in the 1987 or 1994 earthquakes were recognized before the events, Our inability to recognize the structures before the earthquake is a testament to the inadequacies of present geologic data and the non-uniqueness of structural models. An important question is whether more detailed analyses on the San Fernando Valley before the Northridge earthquake would have allowed us to recognize that concealed fault without a major event.

Distributions of microseismicity can delineate the three-dimensional structure of fault systems and these studies have defined both north- and south-dipping fault systems beneath the Los Angeles basin (7). This type of study had not been conducted near the Northridge earthquake before it happened and none of the geologic studies of the San Fernando Valley had recognized a major south-dipping fault. Analysis of the secondary zones of deformation produced in the Northridge earthquake may provide important constraints on models of concealed thrust faults. Recognition and analysis of such features in other regions potentially could provide a method to assess the activity and recurrence intervals of earthquakes on concealed faults.

Geodetic data revealed rapid motion at the northern margin of the Northridge rupture *(11)* and the style of faulting was consistent with these data. interpretation of geodetic data, in conjunction with studies of microseismicity and geologic models, should prove to be a powerful method for hazard assessment (17). However, because no one fault dominates the deformation of this region, hazard mitigation efforts that focus on avoiding one or a few fault structures are not appropriate. With scores of faults, each moving no more frequently than once or twice a millennium, the approach to mitigation must be regionally based. Because of the difference between human and geologic time scales, the most active fault need not, and probably will not, be the fault that ruptures in our lifetime. For instance, the Northridge earthquake raised the northern San Fernando Valley by several centimeters, but the Valley is a valley, arguing that other earthquakes must be lowering this region more often than this earthquake lowers it. Earthquake hazard mitigation in Los Angeles must take all these faults into account.

prior to earthquake

While planning for the earthquakes that will occur on the thrust faults of the Big Bend Compressional Zone, we must not forget the significant earthquake risk in southern California from the large or great earthquakes along the San Andreas fault. The full extent of the urban corridor from San Bernardino through Los Angeles, and northwest to Santa Barbara is at risk from both the thrust faults and the San Andreas fault and the two risks are comparable. The earthquake history of the San Andreas fault suggests that part of the San Andreas fault nearest to Los Angeles, the Mojave segment, produces great earthquakes on average every 131 years *(45)*. The individual concealed and surficial thrust faults in the Big Bend Compressional Zone move more slowly, the necessary geological data are difficult to obtain in an urban setting and their earthquake history is in most cases unknown. However, estimates of the slip over all the faults in Los Angeles from geologic information suggest that earthquakes as large as Northridge must occur on average every 40 years somewhere in the Los Angeles region *(20)*.

The rate of earthquakes actually recorded in Los Angeles since 1800 cannot account for this accumulation. Three possible explanations for this discrepancy arc 1) that the rate of the last 200 years is anomalously low and in the future, moderate earthquakes will be more common, *2)* Los Angeles is accumulating slip to be released in a much larger earthquake of M7.5 or larger, or 3) that significant geologic slip is occurring aseismically. Further studies may help us differentiate between these three possibilities. This has become more crucial because of the present increase in seismicity in southern California, a doubling in the rate of M≥5 events, especially in Los **Angeles** *(46)*. We do not know why the rate of seismicity has increased, but until we have evidence that the rate has changed again, we must consider the rate of the last decade -- almost one M≥5 earthquake per year in the Los Angeles area -- to be the best estimate of the seismic hazard in the next few years.

Does this [illegible] possible Mag-5 Northridge aftershocks?

Slip on the Northridge fault plane undoubtedly changed the static stresses on nearby faults, including the San Andreas fault. Calculations suggest that if the frictional strength of the San Andreas fault is low (47) then a 50-km long segment of the San Andreas fault north of Palmdale was slightly relaxed by Northridge-induced stress changes, and a 30-km long segment south of Palmdale was slightly more loaded. These types of stress changes have affected the rate of microseismicity after large earthquakes in the San Francisco region *(48)*. If the nucleation point for the next large earthquake on the San Andreas fault lies in either the relaxed or the more loaded segment, then that earthquake might be delayed or advanced, respectively, by 2-3 years, based on comparing the magnitude of the Northridge-induced stress changes with the normal tectonic loading rate for this part of the San Andreas fault, If the nucleation point is in neither of these segments, then the Northridge earthquake is not likely to have had much effect at all on the timing of the next Big One, although post-Northridge aseismic afterslip or relaxation in the region might considerably alter the stress distribution over time.

The Northridge earthquake raises the question as to whether the current building code adequately represents earthquake loading and structure behavior. (The Uniform Building Code is in use in California.) The "code earthquake" is intended to be the maximum one with some reasonable chance of occurring. The ground motions from the Northridge earthquake exceed the code earthquake, especially for higher frequencies. Such ground motions must be regarded as the norm in the epicentral region of a large thrust earthquake. Furthermore, because earthquakes larger than Northridge will occur, other possible deficiencies in the code earthquake may exist such as insufficient consideration of long-period ground motion, near-fault ground motions, and duration effects. The behavior of structures is inadequately represented in the code because of a lack of knowledge; the steel connection fracture problem is one example from the

Northridge earthquake. Conclusions about code adequacy based on building performance have to be made carefully. Behavior of older structures may not be relevant for current codes. Also, for strong shaking, damage is to be expected (even in new structures and possibly damage that is unrepairable) since the goal of a building code is to prevent life loss by preventing collapse. Design mistakes and construction flaws must be sorted out as well.

The focus of current design practice solely on avoiding collapse may warrant rethinking in California. Nonstructural damage caused more than half of the financial losses in the Northridge earthquake and the present rate of seismicity suggests that similar earthquakes can occur several times in a normal lifetime. Encouraging simple, cost-effective mitigation among members of the public, such as securing computers, water pipes, ceiling tiles and bookcases, could save billions of dollars in future earthquakes. Nontraditional technologies such as base isolation have much promise in reducing property losses and maintaining functionality after the event, and development should continue. Engineers need to devise methods for limiting damage that can be offered as design options.

The widespread ground failure caused by the Northridge earthquake was similar to the ground failures caused by the 1989 Loma Prieta earthquake, although neither had any direct connection to the causative fault. These types of deformation are, in part, related to near surface geologic conditions that can be identified and mapped for all urban areas of California. Such hazard identifications should become part of future land use planning practices.

Large earthquakes will occur again in southern California. Almost 100 faults in the Los Angeles metropolitan area have been identified as capable of damaging, $M \geq 6$ earthquakes (6), and more are probably still unmapped, but only a few of these, and we do not know which, will produce events in our lifetimes. The mitigation strategies for this heavily populated metropolitan area should focus on recognizing that large earthquakes in the urban areas are not very rare events, predicting the effects of these earthquakes, and designing buildings and response strategies that adequately account for these effects.

Conclusions

The 1994 Northridge earthquake has forcefully brought home two important discoveries of the last two decades in seismology. First, it emphasized the complexity of seismic deformation within the broad fold and thrust belt adjacent to the Big Bend of the San Andreas fault and dramatically demonstrated the threat posed by concealed faults in the Los Angeles Basin. By definition, these faults cannot be mapped at the surface, However, because of their urban setting, they are potentially the most dangerous faults for Los Angeles. Analysis of microseismicity and detailed mapping of the overlying folds are needed to better understand the hazard they represent. Second, the Northridge earthquake provided the largest ever data set of near-field strong motion recordings and proved unequivocally that ground accelerations close to the force of gravity are possible from moderate ($M<7$) earthquakes, and perhaps more importantly, ground velocities can exceed 1 m/s. These data will allow a more detailed examination of the role of site effects on ground motion. Moreover, because of the very large numbers of buildings shaken by this earthquake, engineering results on what determines the extent of damage to buildings and other structures may be the most important advance for seismic hazard mitigation. This earthquake also highlighted some of the still poorly understood aspects of the earthquake process, especially how an earthquake starts, how it stops and what controls the dynamic and static stress drops of an earthquake. The Northridge earthquake confirmed many of the seismological research results of the last two decades. These predict that the ground motions experienced in this earthquake will probably occur again in the lifetime of many residents Los Angeles.

Notes and References

(1) Magnitude calculated from seismic moment (T. Hanks and H. Kanamori, *J. Geophys. Res.*, **84**, 2348 (1979)) is considered more representative of the size of an earthquake and is 6.7 for Northridge. The local Richter magnitude that saturates and thus underestimates the magnitude above M6 was M_L 6.4 determined from TERRAscope data by H. Kanamori. The National Earthquake Information Center (NEIC) assigned the earthquake a 20-s surface-wave magnitude (M_S) of 6.8.

(2) *North ridge Earthquake January 17, 1994: Preliminary Reconnaissance Report*, Earthq. Engin. Res. Inst., J, Hall editor, 1994. The dead included 20 who died from structural failures of their buildings, including 16 at the Northridge Meadows apartment complex and 13 who died from non-structural causes, such as fires, electrocution and falls. Over 30 fatalities from heart attacks have also been attributed to the earthquake,

(3) Personal communication, California Governor's Office of Emergency Services.

(4) The resealed NUVEL-1 rate for relative motion between the Pacific and North American plates at this latitude is 44.5 mm/yr in the N38°W direction. The NUVEL-1 poles are from (Demets, C., R. G. Gordon, and S. Stein, *Geophys. J. Int.*, 101,425, 1990). About 8 mrn/yr of this relative motion occurs along the Eastern California Shear Zone extending into the Basin and Range (Savage, J. C., M. Lisowski, and W. H. Prescott, *Geophys. Res. Let.*, 17, 2113, 1990). The plate motion can be partitioned into a San Andreas fault-parallel component of 32.2 mm/yr (using the average N66°W trend of the San Andreas fault directly adjacent to Northridge) and a fault-normal component of 17.1 mm/yr in a N24°E direction.

(5) The understanding of this system is rapidly evolving with new results so no one paper provides a definitive overview. The surface geology is well described in *(6)* and the seismotectonics in *(7)*.

(6) Ziony, J. I., and R. F. Yerkes, 1985, in *Evaluating Earthquake Hazards in the Los Angeles Region - An Earth-Science Perspective, U. S. Geol. Sum. Prof. Pap. 1360, 43.*

(7) Hauksson, E., *J. Geophys. Res.,* 95,15,365,1990.

(8) Crook, R. J., C. R. Allen, B. Kamb, C. M. Payne, and R. J. Proctor, in *U. S. Geol. Surv. Prof. Pap. 1339, 27,* 1987.

(9) U. S. G. S. Staff, in *The San Fernando, California, Earthquake of February 9,1971, U. S. Geol. Surv. Prof. Pap.* 733, p. 55,1971.

(10) Yeats, R. S.,). *Geophys. Res.,* 88,569-583,1983.

(11) Donnellan, A., B. H. Hager, and R. W. King, *Nature,* 366,333,1993.

(12) Yeats, R., *J. Geophys. Res.,* 93,12,137,1988.

(13) Dibblee, T. W., Jr., 1992, Dibblee Geological Foundation Map #DF-36, and Shields, K. E., 1977, M.S. Thesis, Ohio University.

(14) Hauksson, E., and L. M. Jones,). *Geophys. Res.,* 94,9569, 1989; Hauksson, E., L. M. Jones, T. L. Davis, L. K. Hutton, A. G. Brady, P. A. Reasenberg, A. J. Michael, R. F. Yerkes, P. Williams, G. Reagor, et al., *Science,* 239,1409,1988.

(15) Davis, T. L., J. Namson, and R. F. Yerkes, *J. Geophys. Res.,* 94,9644,1989.

(16) Concealed faults are fault planes that do not crop out at the earth's surface but instead are capped by folds that accommodate the fault's slip in non-brittle deformation. The slip rates on these faults can be inferred from growth rates of the overlying folds (Stein, R. S., and King, G. C. P., *Science,* ***224, 869,*** 1984; Stein, R.S., and Yeats, R. S., *Scientific American,* 260 June, 48,1989.

(17) Ward, S., *Bull. Seismol. Sot. Am.,* in press, 1994; Wesnousky, S. G., *J. Geophys. Res.,* 91, 12,587-12,632, 1986

(18) In term of the potential for moment release from earthquakes of M≥6.5 (Jackson, D., *Seismol. Res. Lets.,* 65, AS, 1994 (abst)). The region was assigned such a high value because of the high geodetic rates of closure.

(19) Seismic risk is defined as the hazard times the exposure where hazard is the potential for a damaging level of earthquake shaking and the exposure is the potentially darnagable structures in that region.

(20) Hauksson, E., in Engineering Geology Practice in Southern California, South. Calif. Sec. Assoc. Engin. Geol., 167,1992.

(21) Based *on* Heaton's (*Bull. Seism. Sot. Amer.,* 72, 2037, 1982) moment of 1.3 x 10^{26} dyne-cm. The local magnitude of the 1971 event was 6.4 the same as Northridge.

(22) Hanks, T. C., 1974, *J. Geophys. Res,* 79,12.15.

(23) Whitcomb, J. H., 1973, in *The San Fernando, California, Earthquake* of *February* 9, 1971, U. S. *Geological Survey Professional Paper 733,30.*

(24) The 1991 Sierra Madre (M5.8) earthquake, Hauksson, E., *Bull. Seism. Soc. Amer.*, in press, 1994.

(25) The Elysian Park system as defined by *(7)* has included the 1987 Whittier Narrows (M5.9) earthquake *(14)* and the 1979 (M5.2) and 1989 (M5.0) Malibu earthquakes (Hauksson, E., and G. M. Saldivar, *J. Geophys. Res.*, 94, 9591, 1989).

(26) The 1988 (M5.0) Pasadena earthquake Jones, L. M., K. E. Sieh, E. Hauksson, and L. K. Hutton, *Bull. Seism. Soc. Amer.*, 80,474, 1990.

(27) Based on a study of small earthquakes in the region from 1980-1992, (Seeber, L., *Seismol. Res. Let.*, 65, A1O, 1994 (abst)).

(28) Slip on a concealed fault plane must be inferred from indirect measurements. Data from many sources, including seismological body and surface waves, local strong ground motions, displacements measured by the Global Positioning System (GPS), and leveling lines can be inverted to estimate the distribution of slip. The details of the distribution vary depending on the data sets and model assumptions. The results described in the text are the robust features common to all of the models so far.

(29) The aftershock data were collected and analyzed by the Southern California Seismographic Network operated by ('California Institute of Technology and the U. S. Geological Survey.

(30) Unlike after the larger 1992 Landers earthquake (Hill et al., *Science*, 260, 1617, 1993), no widespread increase in seismicit y was observed at regional distances after the Northridge mainshock. However within the coda of the Northridge mainshock a few, small (M<1) local events were observed at Medicine Lake, east of the Long Valley Caldera, and several were observed in the Geyser's geothermal area. The Geyser's geothermal field has had increased seismicity after 6 regional events but not after 22 others, depending on the distance from the Geysersto the mainshock and the mainshock magnitude (Davis, S. D., *Trans. Amer.. Geophys. U.*, 74,317, 1993 (abst)). Northridge should have been too small to have triggered a swarm, so other factors may be important. The Geyser's has a high and fairly constant level of seismicity suggesting that it is in a meta-stable condition, always prone to triggering from small perturbations such as the dynamic shaking of regional events. Other areas such as the Long Valley Caldera have more episodic seismicity and may not always be ready to be triggered.

(31) Reasenberg and Jones *(Science*, 243,1173, 1989) showed that the rate at which aftershocks occur after mainshocks can be described by: $\lambda(t,M) 10^{(a+b(M_m-M))}(t+c)^{-p}$ where λ is the rate, t is time, M is magnitude of an aftershock, Mm is the magnitude of the mainshock, and a, b ,c, and p are constants. a is the overall productivity of the sequence, b is the frequency of magnitudes, p is the rate at which the aftershocks decay with time and c is the time delay until the sequence starts to decay. Once these four parameters are

determined for a sequence, the rate of aftershocks is fully described and the probability of future aftershocks can be determined. The parameters for Northridge are almost exactly average for California aftershock sequences except for the high overall productivity, a:

	a	b	c	p
Northridge	-1.3	0.90	0.09 days	1.2
Californian average	-1.67	0.91	0.05 days	1.08
San Fernando 1971	-2.2	1.08		1.2
Long Beach 1933	-1.0	1.0		1.3

(32) The data have been collected by California Strong Motion Instrumentation Program, Report OSMS 94-01 through 94-05, 1994; Porcella, R., E. Etheridge, A. Acosta, E. Anjal, L,. Foote, and W. Jungblut, U.S. Geol. Surv., National Strong-Motion Network, Prelim. Rept., 1994; Trifunac, M. D., M. 1, Todorovska and S.S. Ivanovic, *Int. J. Soil Dynamics and Earthquake Engineering,* in press, 1994.

(33) Boore, D. M., W. B. Joyner, and T. E. Fumal, 1993, U. S. Geol. Surv. Open-File Rept. 3-509, 72 p; Joyner, W. B., and D. M. Boore, *Bull. Seism. Soc. Am.,* 71, 2011, 1981; Brillinger, D. R. and H. K, Preisler, *Bull. Seism. Sot. Am.,* 74, 1441, 1984: ibid, *Bull. Seism. Soc. Am.,* 75,611,1985.

(34) e.g., Hanks, T.C. and R. A. McGuire , *Bull. Seism.* Sot, *Am.,* 71, 2071, 1981; Boore, D. M., *Bull. Seism. Sot. Am.,* 73,1865, 1983; ibid, *Bull. Seism Sot. Am.,* 76, 43, 1986. These studies model the earthquake source in terms of moment magnitude and a parameter, called the stress parameter, which controls the dynamic ground-motion amplitudes. Preliminary modeling of Northridge data using the frequency dependent Q = 61xfrequency(Hz) from earlier analysis of acceleration spectra for the San Fernando earthquake (Papageorgiou, A. S. and K. Aki, *Bull. Seism. Sot. Am.* 73, 953, 1983) compared the observed peak horizontal accelerations at rock sites (to avoid possible non-linear effect) with those predicted for a single co-squared model with fmax = 10Hz using the site amplification factor estimated by the coda method (Su, F., K. Aki, T. Teng, Y. Zeng, S. Koyanagi and K. Mayeda, *Bull. Seism. Soc. Am.,* 82, 580, 1992 and Chin, B. H., and K. Aki, *Bull. Seism. Sot, Am., 81,* 1859, 1991). The "stress parameter" of the best fitting model was about 150 bars, which is two to three times the representative value for the western U. S. (Atkinson, G. M. and Boore, D. M., *Earthquake Spectra,* 6, No. 1,15, 1990).

(35) The velocity of rupture propagation is very nearly the same as the velocity of shear-wave propagation. As a consequence, if the rupture propagates toward a station, radiation from a relatively long portion of the rupture arrives at the station in a relatively short time compared to stations at other azimuths, hence the ground motions amplitudes are larger. In turn, a station located away from the propagation direction will record a more elongated wave train with less severe ground motion.

(36) The shear motion across a fault leads to a nonhomogenous distribution of energy radiation from an earthquake. Santa Monica was in the direction of maximum S-wave radiation while in comparison, Pasadena was at a minimum in both P and S waves.

(37) The velocities are determined from integration of acceleration records. A glitch in the film record at the Rinaldi station, interpreted as a stall in the advancing mechanism, makes the temporal integration uncertain. The value of 170 cm/s assumes that the film stalled for 0.05 s. Assuming no stall gives a minimum estimate of 130 cm/s. Any longer delay would imply an even greater velocity.

(38) The most extreme local geologic site effect in the Northridge earthquake was recorded in Tarzana with a peak horizontal acceleration of 1,82 g. In the 1987 Whittier Narrows earthquake, the same site had a peak horizontal acceleration of 0.62 g, more than ten times greater than the geometric mean of seven values at similar distance in that earthquake. In other events, including a Whittier Narrows aftershock, the peak horizontal acceleration at this site was not especially large. Since the nearby nursery and homes in the area did not seem to experience any unusually high damage, the large peak acceleration must have been caused by very localized amplification. Given that this extremely high amplitude recording was made at a soil site, it calls into question that non-linear effects always limit the peak acceleration in soils.

(39) Hanks, T. C., *Bull. Seism. Soc. Am.*, 65,193, 1975; Drake, L. A., *Bull. Seism. Soc. Am.*, 70,571, 1980; Liu, H.-L. and T. H. Heaton, *Bull. Seism. Soc. Am.*, 74, 1951, 1984; Vidale, J. E. and D. V. Helmberger, *Bull. Seism. Soc. Am.*, 78, 122, 1988

(40) Unequivocal evidence for liquefaction, primarily the venting of sand and water to the surface, was not observed in association with these ground fractures except for a few isolated occurrences in Potrero Canyon, along the north flank of the Santa Susana Mountains. However, studies are in progress to assess whether much of the observed deformation could have resulted from liquefaction at depth that did not expel sand.

(41) Ground fractures were largely the cause of numerous breaks in water and gas lines, including the rupture and explosion of a 22” gas main in Granada Hills that destroyed five homes. Permanent ground deformation was also wholly or partially to blame for extensive foundation damage to hundreds of homes in the San Fernando Valley.

(42) The duration of rupture in the 1971 earthquake was 10-12 s (Heaton, T. H., 1982, *Bull. Seismol.* Sot, *Amer.*, 72, 2037-2062) compared to 6-8 s for the Northridge earthquake. Each shaking cycle increases the compaction of soils so that duration is an important factor controlling liquefaction (Youd, T. L., 1972, *J. Soil Mech. and Found ations Engin., 98, 709.).*

(43) Tinsley, J. C., T. L. Youd, D. M. Perkins, and A. T. F. Chen, in *Evaluating Earthquake Hazards in he Los Angeles Region - An Earth-Science* Perspective, U. S. *Geol. Surv. Prof. Pap.* 1360, ed. J. Ziony, p. 263,1985.

(44) Yeats, R. S., 1994, Nature, submitted; Davis, T. L., and J. Namson, 1994, Nature, submitted.

(45) Sieh, K. E., M. Stuiver, and D. Brillinger, 1989, *J. Geophys. Res.*, 94,603-624.

(46) Since 1900, moderate (M>4.8) earthquakes in the Los Angeles region have occurred in 2 clusters with 5 events between 1920 and 1942 and 10 events so far since 1970. No moderate events were recorded between 1942 and 1970. All the earlier events were located in the southern Los Angeles basin while all the recent earthquakes have been on the north flank of the basin *(20)*. Previous changes in the rate of moderate earthquakes in California have in some cases, been followed by major earthquakes (such as the 1906 M8 San Francisco, 1983 M6.5 Coalinga and 1989 M7.1 Loma Prieta events). In other cases, such as the Long Valley area 1978-1986 and the Banning region of southern California 1935-1948, no one event within the sequence is significantly larger than the others, while in the earlier Los Angeles cluster, the largest event (1933 M6.4) Long Beach was in the middle of the group. The mechanisms controlling rate changes or relating them to the largest earthquakes of a region are not clearly understood.

(47) Zoback, M. D., et al., 1987, *Science,* 238,1105-1111.

(48) These faults are ones for which the failure criterion has been moved towards failure by at least 0.1 bar. Stress changes of this level have been shown to affect seismicity levels in the San Francisco region (Reasenberg, P. A., Simpson, R. W., 1992, *Science,* 255, 1687).

(49) Jennings, C. W., 1975. Fault Map of California with Volcanoes, Thermal Springs and Thermal Wells (Scale 1:750.000), California Division of Mines and Geology Geologic Data Map No. 1.

(50) Acknowledgements. This research has been funded by the National Science Foundation through the Southern California Earthquake Center, the U. S. Geological Survey, and the National ~~Space and Atmospheric~~ Administration. SCEC Publication number, Cal tech publication#. Aeronautics and Space Administration.

Figures

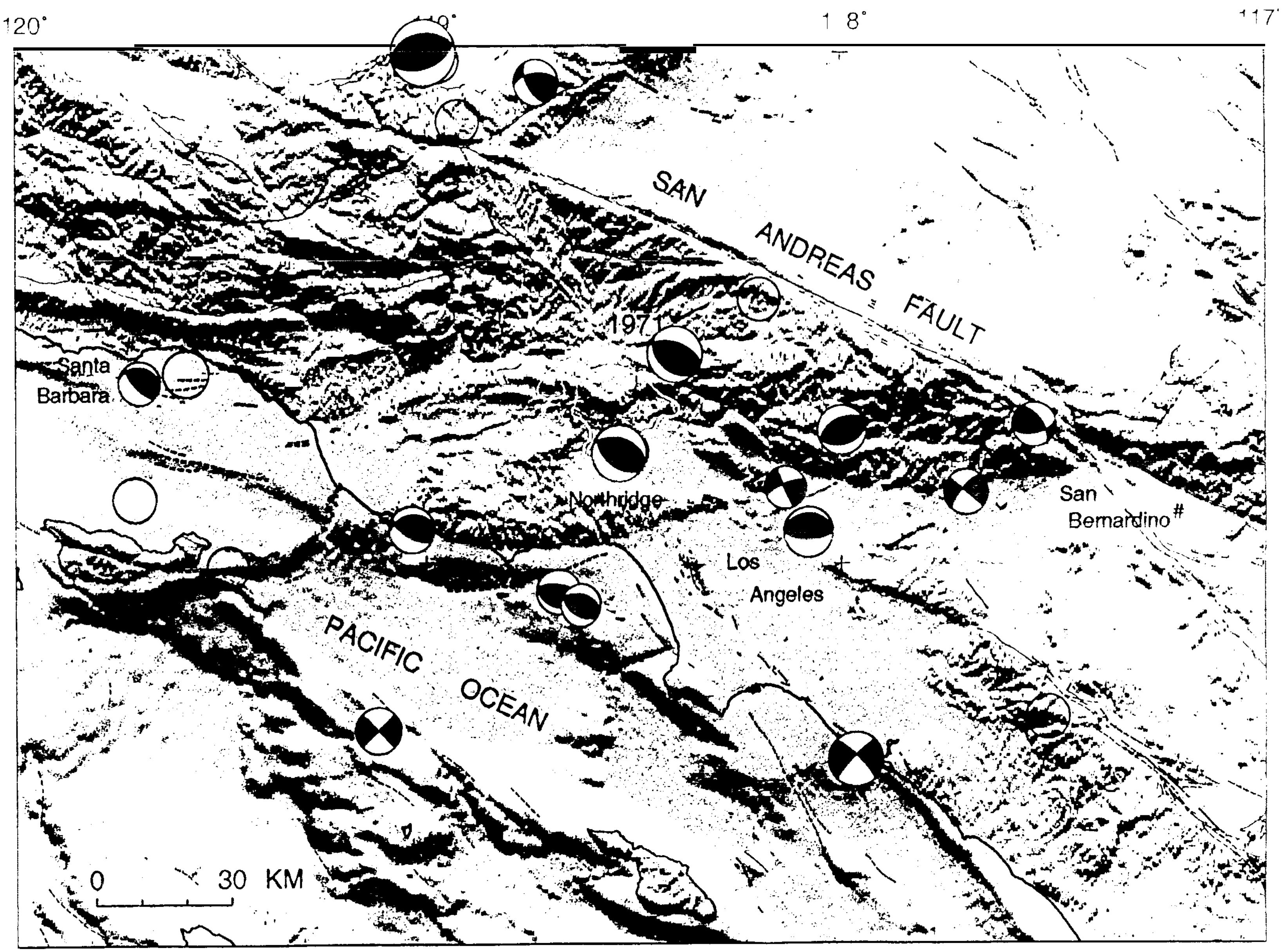
Fig. 1. A digital shaded relief map of southern California topography produce from U.S.G.S. topographic data files, faults and M≥5.0 earthquakes since 1932. The earthquakes are shown by lower hemisphere focal mechanisms with size proportional to magnitude and compressions] quadrants shaded if the mechanism is known, and by open circles when it is not known. The mechanism of the 1994 Northridge earthquake is shown in red and an outline of its aftershock zone is in yellow.

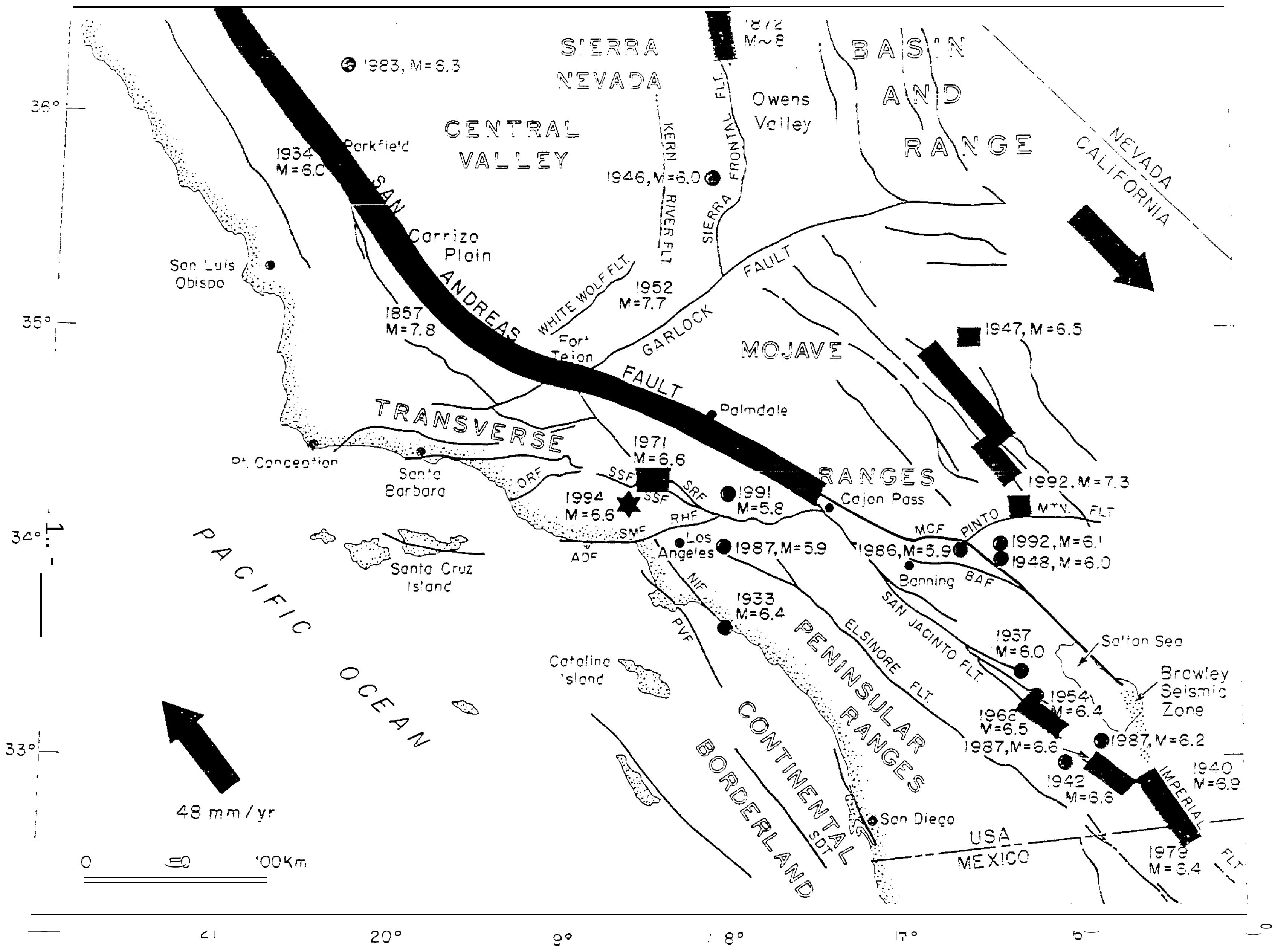
Fig. 2. A map of southern California showing the major faults and physiographic regions and the $M_L \geq 6.0$ earthquakes recorded from 1932 through 1993. Historic fault rupture is shown in red. Large arrows indicate the sense and magnitude of plate motion. Some fault names are abbreviated as: ADF = Anacapa Dume fault; BAF = Banning fault; CF = Cucamonga fault; MCF = Mission Creek fault; ORF = Oak Ridge fault; PVF = Pales Verdes fault; RHF = Raymond Hill fault; SDT = San Diego Trough-Bahia-Soledad fault; SFF = San Fernando fault; SMF = Santa Monica fault; SRF = Sierra Madre fault; SSF = Santa Susana fault. ADD SAN CAYETANO

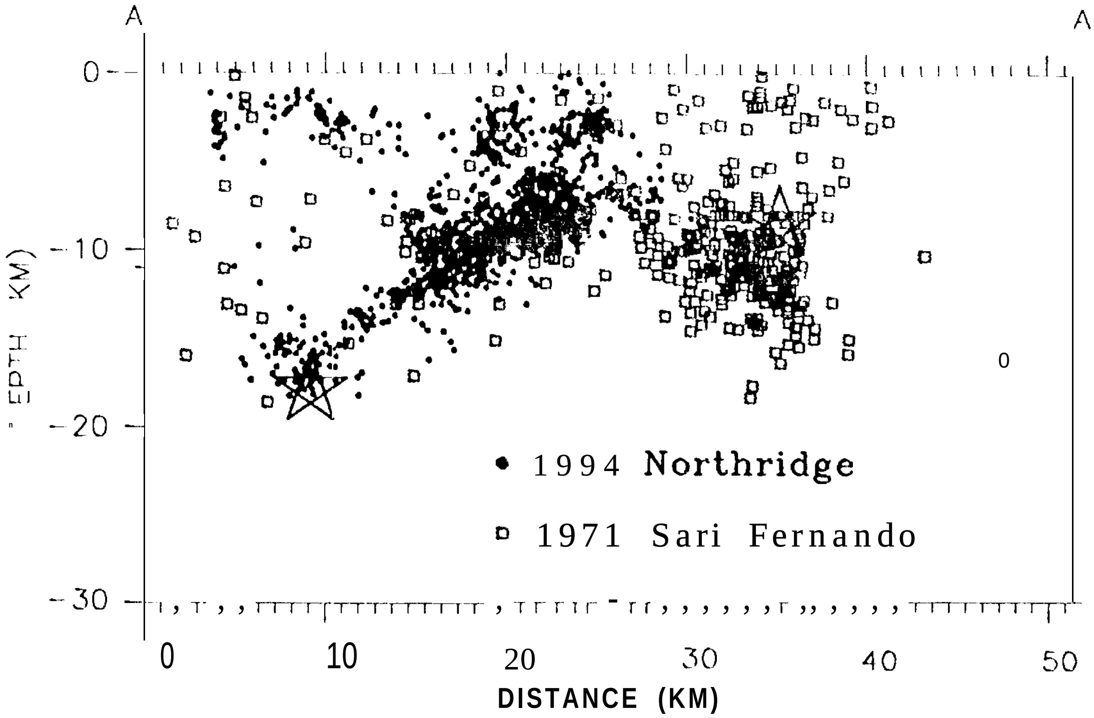
Fig. 3. a) A map showing epicenters of the Jan. 17, 1994 Northridge earthquake and its aftershocks (in red) and the Feb. 9, 1971 San Fernando earthquake and its aftershocks (in blue) with faults from *(50)*. b) A cross section of the hypocenters in Fig. 3a projected onto a line trending N30°E.

Fig. *4.* A digital shaded relief map of southern California topography produce from U. S.G.S. topographic data files showing data from the 1994 Northridge earthquake including zones of ground deformation, geodetic horizontal displacements and contours of uplift, most of the liquefaction sites (some may not have been included in the early reporting), and measurements of peak ground accelerations.

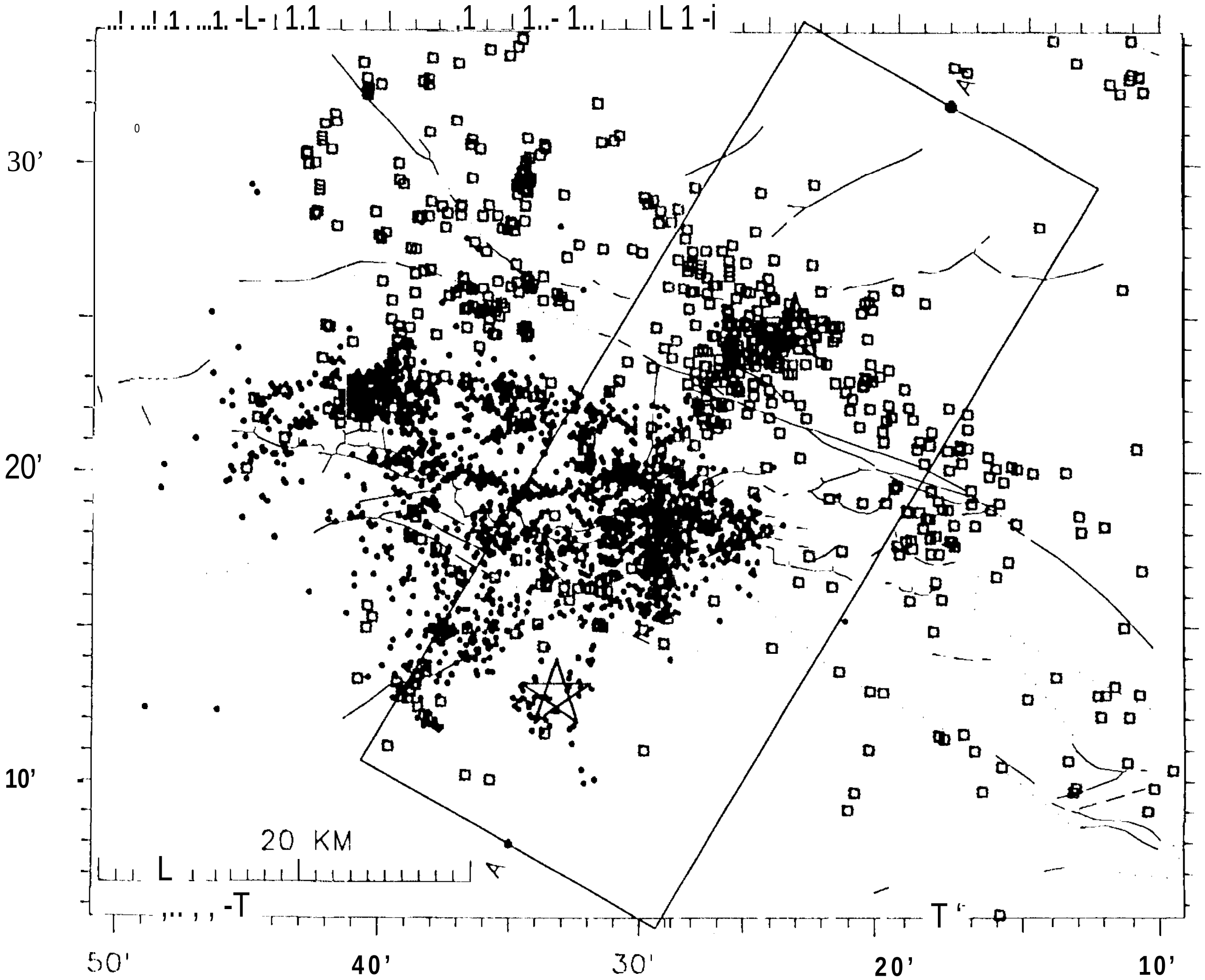
Fig. 5 The larger peak of the two horizontal components of acceleration in the Northridge earthquake (filled circles) *(34)* compared with the median and ± one-standard-deviation curves given by the equations of *(38)* for a moment magnitude 6.7 earthquake and site Class B, that we believe are representative of typical Northridge sites. The acceleration data are plotted against the closest horizontal distance to the rupture defined by the GPS data (Fig. 4). We plot only sites whose motion is judged to be unaffected by structures they are on or near. The open circles show values from the 1971 San Fernando earthquake.


120°
117°
SAN ANDREAS FAULT
1971
Santa Barbara
Northridge
Los Angeles
San Bernardino
PACIFIC OCEAN
0 30 KM

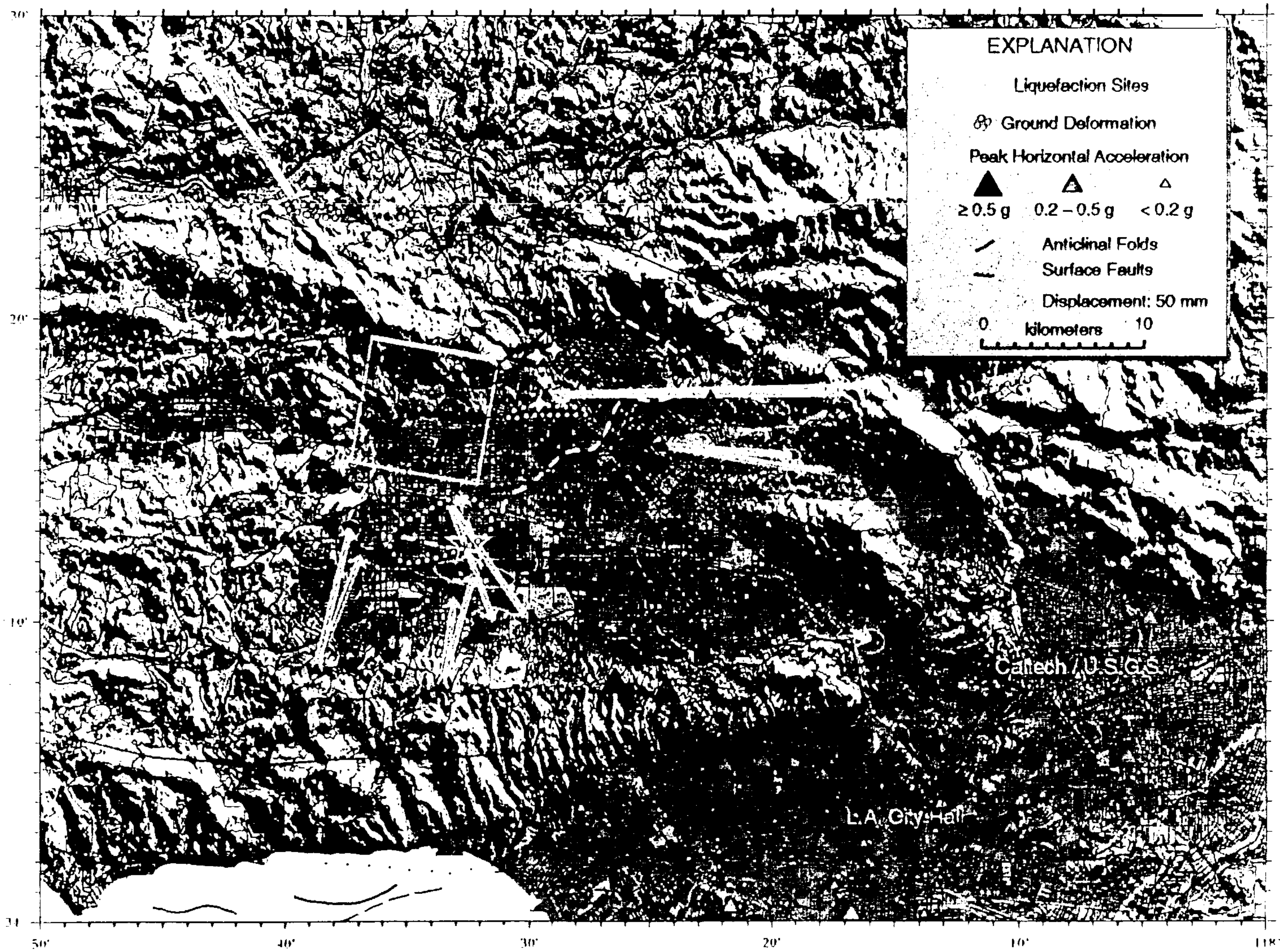

SIERRA NEVADA
CENTRAL VALLEY
BASIN AND RANGE
NEVADA
CALIFORNIA
1983, M=6.3
M~8
Owens Valley
1934 M=6.0
Parkfield
SAN ANDREAS FAULT
1946, M=6.0
KERN RIVER FLT.
SIERRA FRONTAL FLT.
Carrizo Plain
San Luis Obispo
WHITE WOLF FLT.
1952 M=7.7
GARLOCK FAULT
1857 M=7.8
Fort Tejon
MOJAVE
1947, M=6.5
Palmdale
TRANSVERSE RANGES
Pt. Concepcion
Santa Barbara
ORF
1971 M=6.6
SSF
SRF
1991 M=5.8
Cajon Pass
1992, M=7.3
MTN. FLT
PINTO
1994 M=6.6
RHF
SMF
ADF
Los Angeles
1987, M=5.9
MCF
1986, M=5.9
1992, M=6.1
1948, M=6.0
Banning
BAF
PACIFIC OCEAN
Santa Cruz Island
NIF
1933 M=6.4
PVF
Catalina Island
PENINSULAR RANGES
ELSINORE FLT.
SAN JACINTO FLT.
1937 M=6.0
Salton Sea
Brawley Seismic Zone
1954 M=6.4
1968 M=6.5
1987, M=6.2
1987, M=6.6
1942 M=6.6
1940 M=6.9
IMPERIAL FLT.
CONTINENTAL BORDERLAND
SDT
San Diego
USA
MEXICO
1979 M=6.4
48 mm/yr
0
50
100Km
36°
35°
34°
33°
20°

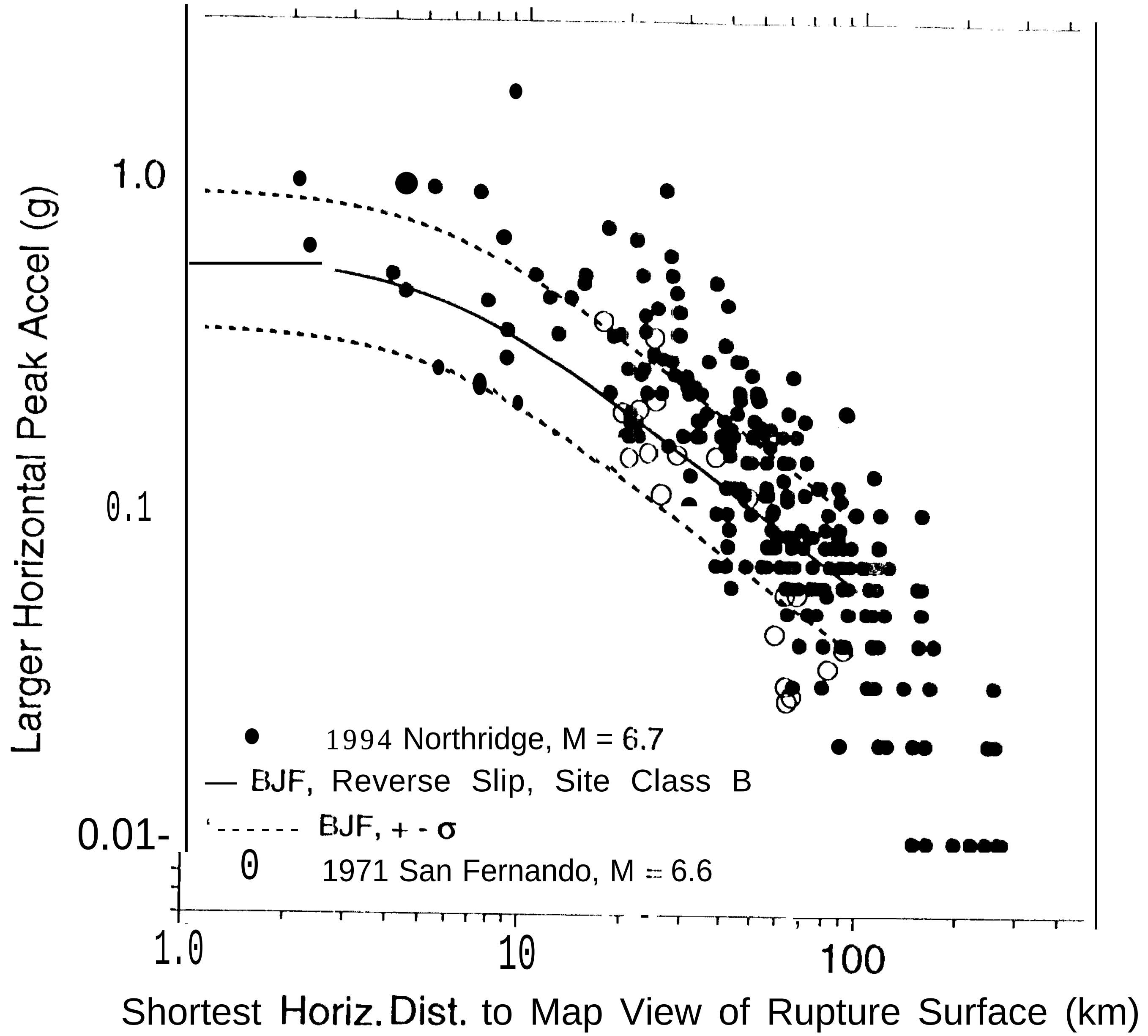


A
A'
0
-10
-20
-30
EPTH (KM)
1994 Northridge
1971 Sari Fernando
0
10
20
30
40
50
DISTANCE (KM)



30'
20'
10'
20 KM
A
A'
50'
40'
30'
20'
10'


EXPLANATION
Liquefaction Sites
Ground Deformation
Peak Horizontal Acceleration
≥ 0.5 g
0.2 – 0.5 g
< 0.2 g
Anticlinal Folds
Surface Faults
Displacement: 50 mm
0 kilometers 10
Caltech / U.S.G.S.
L.A. City Hall
50'
40'
30'
20'
10'
118°
30'
20'
10'



(Rupture surface is given by M. Murray's inversion of GPS data, as of 2/16/94.)

Mar 10, 1994 12:07:32 pm   \psv\norridge\nrsflpab.gra   D. M. Boore